

ACTIVE GALAXIES AND THE STUDY OF BLACK HOLE DEMOGRAPHICS

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ABSTRACT

We discuss the critical importance of black hole mass indicators based on scaling relations in active galaxies. We highlight outstanding uncertainties in these methods and potential paths to substantial progress in the next decade.

1. BLACK HOLE DEMOGRAPHICS AND ACTIVE GALAXIES

The most reliable measures of black hole (BH) mass are derived from spatially resolved dynamical tracers, the stars at the center of our own Galaxy providing the most precise BH mass measurement (e.g., Ghez et al. 2008; Gillessen et al. 2009) followed closely by water masers in Keplerian rotation fractions of a parsec from the central BH (e.g., Herrnstein et al. 2005). Stellar and gas dynamical models use the integrated light from stars or gas in the centers of nearby, relatively inactive galaxies to infer BH masses with $\sim 30\%$ precision (e.g., Gebhardt et al. 2003), although potential systematics due to, e.g., the varying importance of dark matter as a function of galaxy mass are not yet well known (e.g., Gebhardt & Thomas 2009). The advent of the *Hubble Space Telescope* has enabled the measurement of dynamical BH masses in dozens of nearby massive galaxies, which in turn has revolutionized our understanding of BH demographics. It has become clear that not only are supermassive BHs a ubiquitous component of bulge-dominated galaxy centers (e.g., Ho 2004), but that apparently the evolution of the BH and the surrounding bulge are coupled, as evidenced by the remarkably tight correlations between BH mass and the properties of the surrounding bulge, particularly bulge velocity dispersion (the $M_{\text{BH}} - \sigma_*$ relation; e.g., Gültekin et al. 2009).

Given the apparent cosmological significance of supermassive BHs in the evolution of galaxies, we are highly motivated to study the demographics and growth histories of BHs beyond the Local Universe. Unfortunately, the dynamical techniques outlined above require very sensitive observations with high spatial resolution, which are currently limited to galaxies within tens of Mpc. Techniques using active galactic nuclei (AGNs), which currently must be calibrated to the direct dynamical methods, are the only means to study the cosmological evolution of BH demographics and accretion. This article addresses the current limitations on indirect BH mass measurements, and experiments that could substantially improve them in the next decade.

2. VIRIAL MASSES IN ACTIVE GALAXIES

As early as Woltjer (1959) it was recognized that if the signature broad emission lines in the spectra of AGNs truly represent gas orbiting the central BH, then they may serve as a virial tracer of the enclosed mass, provided one has a scale for the emission region. A size can be determined from the delay between variability in the central continuum source and the surrounding photoionized gas [known as reverberation mapping (RM); Blandford & McKee 1982; see review in Peterson et al.

2004]. The BH mass scales as the virial product $M_{\text{BH}} \propto R v^2 / G$, but remains uncertain within a scale factor f due to the unknown structure and kinematics of the broad-line region (BLR). Only with the discovery of the $M_{\text{BH}} - \sigma_*$ relation did it become possible to independently cross-check the RM masses, as well as to solve for f in an average sense (e.g., Nelson et al. 2004; Onken et al. 2004).

RM experiments are time consuming, particularly for luminous objects, and have been performed for only ~ 45 objects to date, but, due to a well-defined correlation between AGN luminosity and BLR size (the radius-luminosity relation; e.g., Kaspi et al. 2000; Bentz et al. 2009a) it is possible to estimate so-called virial BH masses from single-epoch AGN spectroscopy. Comparisons between large samples of single-epoch virial masses and σ_* yield reasonable agreement and similar f values as the RM samples (Greene & Ho 2006; Shen et al. 2008a). It is these virial masses that enable study of the demographics (e.g., Greene et al. 2008), mass-dependent clustering (e.g., Fine et al. 2006; Shen et al. 2009), BH mass functions (e.g., Greene & Ho 2007; Kelly et al. 2009b) and Eddington-ratio distributions (e.g., Kollmeier et al. 2006; Shen et al. 2008b; Hickox et al. 2009) for accreting BHs, as well as investigations of the evolution in BH-bulge scaling relations with cosmic time (e.g., Peng et al. 2006).

While the ability to estimate BH masses using the virial method has resulted in substantial progress in our understanding of BH demographics and evolution, the technique is very indirect, and each calibration step introduces a new layer of uncertainty. First of all, the radius-luminosity relation on which the entire architecture rests has been calibrated using only ~ 30 objects. When measured using lags between $H\beta$ and L_{5100} the slope is found to be $\alpha = 0.519^{+0.063}_{-0.066}$ (Bentz et al. 2009a), in agreement with the C IV slope of 0.52 ± 0.04 (Kaspi et al. 2007). However, the formal errors do not properly reflect the true slope uncertainties. Prior to the careful galaxy subtraction performed by Bentz et al., the radius-luminosity relation slope was substantially steeper ($\alpha = 0.67 \pm 0.05$; e.g., Kaspi et al. 2005), while the slope also changes when various objects are removed or included. In our view the most significant outstanding systematic uncertainties in the radius-luminosity relation slope come from the limited scope of the sample. The range in luminosity is only $L_{5100} = 10^{42} - 10^{46}$ erg s⁻¹, with only five and three objects in the lowest and highest decades respectively, while the Eddington ratios are strongly clustered around $\sim 10\%$. There are hardly any radio-loud targets. These biases are present because only a small sample of local, heterogeneous targets se-

lected for their known variability properties have been targeted to date. Ideally, we would like to see BLR measurements for BHs ranging over $10^5 - 10^9 M_\odot$ and at least two decades in luminosity at each mass. *Unbiased virial BH masses require a measurement of the radius-luminosity relation for objects spanning a complete range in BH mass and luminosity.*

Even with a perfect radius-luminosity relation, there is still ambiguity in the overall mass scaling from object to object due to our ignorance of BLR structure. Collin et al. (2006) make a compelling case for systematic changes in the value of f as a function of accretion rate and perhaps BH mass as well. Theoretically, we do expect BLR structure to vary as a function of accretion rate. For instance, the existence and opening angle of disk winds are thought to depend on both M_{BH} and $L_{\text{bol}}/L_{\text{Edd}}$ (e.g., Proga & Kallman 2004). Alternatively, radiation pressure may provide non-negligible support to the BLR gas, thus biasing the virial masses (Marconi et al. 2008) although debate continues on the importance of this effect in practice (e.g., Netzer 2009; Onken 2009). *Independent BH mass estimates are required to calibrate the f factor for objects spanning a complete range in BH mass and luminosity.*

There is one more central concern worth noting here. Rest-frame optical spectra containing Balmer emission-lines are not available for large samples of high-redshift quasars, and we are thus forced to rely on UV lines, specifically Mg II $\lambda 2800 \text{ \AA}$ and C IV $\lambda 1550 \text{ \AA}$ (e.g., Vestergaard 2002; McLure & Jarvis 2002). There is little reverberation mapping done for Mg II, and thus the virial mass scale is simply bootstrapped from H β (Vestergaard & Peterson 2006; see also Onken & Kollmeier 2008). In the case of C IV, reverberation mapping has been performed for a small handful of objects (e.g., Peterson et al. 2005), but the line width may not be dominated by virial motions. It is clear that the scatter between C IV and Mg II or H β line widths is substantial (e.g., Baskin & Laor 2005; Shen et al. 2008), and the overall reliability of C IV as a virial estimator remains a matter of debate (e.g., Kelly et al. 2007). We choose here to focus on improving the Balmer line calibrations, as a necessary step to understanding the UV lines.

3. A WISH LIST

We focus on a few potential avenues for future progress in improving the reliability of BH mass measurements that we believe are achievable with existing or planned instrumentation:

1. Dedicated RM campaigns are required to securely measure the radius-luminosity relation for a large and representative sample of active galaxies. A recent extensive monitoring program at Lick Observatory demonstrates the feasibility of such campaigns (Bentz et al. 2009b; Denney et al. 2009), measuring an additional eight new BLR radii in a low-luminosity regime as yet unexplored. The data are of such high quality that velocity-resolved lags can be measured in a few cases, which may yield measurements of f for individual objects (Bentz et al. 2008, 2009b; Denney et al. 2009).
2. A dedicated spectroscopic monitoring telescope could substantially improve the diversity of the samples used to define the radius-luminosity relation at intermediate luminosities and low redshift. It is convenient to consider three distinct luminosity regimes,

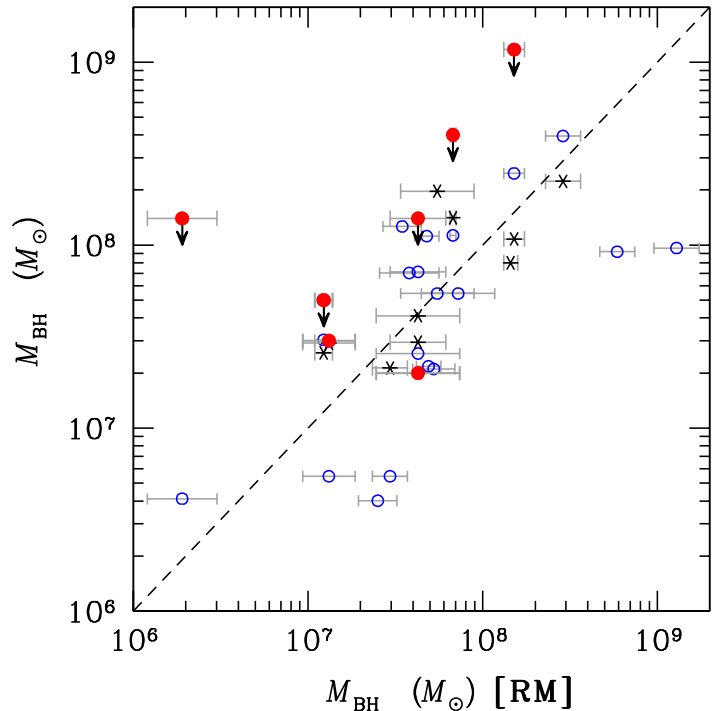


FIG. 1.— Comparison of the masses derived using RM and various other techniques. For simplicity, we adopt the RM sample and mass estimates of Bentz et al. (2009a). Gas-dynamical mass estimates and upper limits (filled red circles) are from Hicks & Malkan (2009), masses inferred from stellar velocity dispersions (open blue circles) are from Nelson et al. (2004), Onken et al. (2004), and Dasyra et al. (2007), and masses from X-ray variability (stars) are from Nikolajuk et al. (2006). The one-to-one relation is shown only to guide the eye (dashed line). Note that the absolute RM mass scale (f) has been set to match a subset of the blue points. NGC 4395, with a RM mass of $\sim 10^5 M_\odot$ (Peterson et al. 2005) and a σ_* -based mass of $\sim 4 \times 10^4 M_\odot$ (Filippenko & Ho 2003) does not appear in the figure only because of the very low mass.

and, for this discussion, luminosity refers to L_{5100} . In general, campaigns should last at least 3 times as long as the maximum timescale that they need to probe (e.g., Peterson 2001), although recent monitoring campaigns demonstrate that ~ 6 times longer is actually preferred in the presence of finite sampling and signal-to-noise ratio (e.g., Bentz et al. 2008). Of course, only a fraction of sources will vary at any given time. Objects with $L_{5100} \lesssim 10^{42} \text{ erg s}^{-1}$ have lags less than one light day and require continuous monitoring with an 8 m-class telescope over a period of at least a week, in order to achieve sufficiently short individual exposures to resolve the lag times but still detect broad-line variability. So far, the only such object with successful RM in this regime is NGC 4395, which was done with C IV $\lambda 1549$ from space (Peterson et al. 2005). For the regime $L_{5100} = 10^{42} - 10^{43} \text{ erg s}^{-1}$, the lags are a few days and the targets should be observed at least every other day for a few months (e.g., Bentz et al. 2008). At $L_{5100} = 10^{43} - 10^{45} \text{ erg s}^{-1}$ the appropriate sampling is \sim weekly for 1–2 years. Objects more luminous require significantly longer baselines, since not only are their BLRs physically larger, but they also tend to reside at $z > 0.5$, causing additional stretching of the observed variability timescale.

The targets requiring daily observations must be monitored photometrically with a dedicated 1 m-class tele-

scope. For more luminous targets the 3–5 day temporal sampling delivered by current and upcoming time-domain surveys (e.g., Palomar Transient Factory, Law et al. 2009; Pan-STARRS¹; LSST, Ivezic et al. 2008) should provide adequate photometry. Assuming a 4 m-class spectroscopic telescope, with a 2'' slit (to minimize light losses in bad seeing conditions) and ~ 10 Å resolution, it should be possible to obtain sufficient S/N in $\lesssim 1$ hr to measure $\sim 10\%$ variability in the H β line for objects with $F_{\text{H}\beta} \gtrsim 10^{-14}$ erg s⁻¹ cm⁻² (e.g., Kaspi et al. 2000). We note that many recent lag measurements have achieved 1% spectrophotometry in the emission lines (e.g., Denney et al. 2006; Bentz et al. 2006, 2008), but such precision is feasible only for a very small number of targets. In the Sloan Digital Sky Survey Data Release 4 (Adelman-McCarthy et al. 2006) at $z \lesssim 0.05$ there are ~ 100 broad-line objects with $L_{5100} = 2 \times 10^{42} - 4 \times 10^{43}$ erg s⁻¹ and $M_{\text{BH}} \approx 10^5 - 10^8 M_{\odot}$ (Greene & Ho 2007). Assuming that 1 hr of integration is spent per observation and that each galaxy needs ~ 90 observations to determine a lag, a two-year dedicated spectroscopic survey could observe more than half of the entire sample, if only one-fifth of the observing time is lost to bad weather. This very crude sketch demonstrates that even with existing modest resources, substantial progress could be made on measurements of the radius-luminosity relation as a function of AGN properties. To significantly expand the dynamic range in luminosities, however, requires both an investment of 8 m-class resources for low-luminosity targets and a much longer campaign to target luminous (and necessarily distant) ones (e.g., Kaspi et al. 2007).

3. In addition to improvements in the radius-luminosity relation, independent measurements of BH mass are needed, again spanning the full mass-luminosity parameter space, with which to calibrate f . To zeroth order f has been calculated by scaling RM or virial masses to match the $M_{\text{BH}} - \sigma_*$ relation (see Fig. 1). In a handful of cases it ought to be possible to constrain the kinematic structure of the BLR using two-dimensional RM in which lags are determined as a function of velocity in the broad line (e.g., Bentz et al. 2008). While expensive, this technique provides a real measurement of BLR structure.

The next obvious step is to amass a sufficiently large sample of stellar velocity dispersions in AGNs, spanning a wide enough range in BH mass, that f can be measured as a function of linewidth and luminosity. Some progress has been made using both near-infrared spectroscopy (e.g., Dasyra et al. 2007) and adaptive-optics assisted integral-field unit spectroscopy (e.g., Watson et al. 2008). With large samples (e.g., 10 objects per decade in mass and luminosity) it should be possible to measure f as a function of M_{BH} and L .

Comparison with $M_{\text{BH}} - \sigma_*$ in the determination of f may well fail if the galaxies in question do not obey the $M_{\text{BH}} - \sigma_*$ relation. It is important to bear in mind that while the range of dynamical BH masses extends over $M_{\text{BH}} \approx 10^6 - 10^8 M_{\odot}$, the majority of the objects

are clustered around $M_{\text{BH}} \approx 10^8 M_{\odot}$. In contrast, the masses of the local active samples range from $\sim 10^5$ to $10^9 M_{\odot}$, and the majority of those with σ_* measurements have $M_{\text{BH}} \approx 10^7 M_{\odot}$. There is some indication that the scatter, and possibly the shape, of the $M_{\text{BH}} - \sigma_*$ relation depend on galaxy type (e.g., Hu 2008; Greene et al. 2008; C. Y. Peng & L. C. Ho, in preparation; Greene, J. E. et al., in preparation). Furthermore, active systems may not obey the $M_{\text{BH}} - \sigma_*$ relation during their active phase (e.g., Ho et al. 2008; Kim et al. 2008). Direct gas or stellar dynamical BH masses are needed to bypass these degeneracies, but so far have been attempted in only a handful of cases (Fig. 1; Davies et al. 2006; Onken et al. 2007; Hicks & Malkan 2008). Of the RM objects with stellar velocity dispersions in hand, nine are close enough to attempt a dynamical measurement (i.e., current adaptive-optics assisted spectrographs can reach to a few times the gravitational sphere of influence of the BH; e.g., Hicks & Malkan 2008). The number should increase with new RM surveys targeting low-luminosity sources (e.g., Bentz et al. 2008). While these numbers are still small, and restricted to $\sim 10^7 M_{\odot}$ BHs, even a few dynamical BH mass measurements would provide a crucial cross-check on RM.

4. Aside from direct dynamical masses and galaxy scaling relations, variability timescales also correlate with M_{BH} . In particular, it has been shown that the characteristic X-ray variability timescale correlates with BH mass (e.g., Czerny et al. 2001; Lu & Yu 2001; Markowitz et al. 2003; ; Nikolaïjuk et al. 2004, 2006; Done & Gierliński 2005). In principle, X-ray variability is completely independent of the $M_{\text{BH}} - \sigma_*$ relation and RM, since the masses are scaled to the variability properties of high-mass X-ray binaries. However, the story may be more complicated, as there appears to be additional dependence on the luminosity or Eddington ratio of the BH (McHardy et al. 2006). At the moment, X-ray power-spectrum analysis has been possible only for a handful of bright local AGNs (e.g., Uttley et al. 2002). Upcoming all-sky X-ray monitors such as *Lobster*² (0.1–3 keV) and *MAXI* (2–30 keV; Matsuoka et al. 2009) will deliver increases of factors of a few in the number of targets with adequate long-term monitoring to explore all scales in X-ray variability. For instance, *Lobster*, with a sensitivity of 0.15 mCrab per day, will monitor ~ 400 AGNs per year with daily cadence and $\sim 20\%$ accuracy, and ten percent of those will have $\sim 5\%$ accuracy. Thus, the opportunities for cross-calibration between X-ray variability, dynamical masses, RM, and virial mass estimates will also increase dramatically.
5. Much like in the X-rays, optical variability timescales are correlated with BH mass, again with a secondary dependence on luminosity (e.g., Collier & Peterson 2001; Kelly et al. 2009a; Walsh et al. 2009). Again, upcoming optical time-domain surveys (see above) will enable cross-calibration of this relatively new technique with large and relatively unbiased samples. We note also that a byproduct of a large RM campaign would be very

¹<http://pan-starrs.ifa.hawaii.edu/public/>

²www.mpe.mpg.de/erosita/MDD-6.pdf

well-sampled optical light curves yielding characteristic optical timescales that can be compared with the RM masses.

In closing, we note that our discussion focuses on observational avenues for improvements in BH mass measurement techniques. While we believe the experiments described above are crucial to tie down the BH mass scale at cosmological distances, they alone are not sufficient. Despite decades of research, we still do not have a complete model for the BLR.

We are hopeful that these experiments, in addition to providing more robust empirical estimators of BH mass, will also provide needed constraints on the kinematics and structure of the line-emitting region as a function of M_{BH} , thereby inspiring more detailed modeling of the physics of the BLR.

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